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Electro Active Polymer-based Dimple Actuators with Ultra-thin Metal Electrode for Flow Control

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Research efforts are being pursued currently at CSIR-NAL towards the development and application of Electro-Active Polymers (EAP) as a micro-actuator for flow control at low Reynolds numbers. Dimple actuators with ultra-thin metal electrodes have been fabricated and demonstrated for their effectiveness in flow separation control on airfoils. This paper describes the design, fabrication, characterization and validation of EAP-based dimple actuators and their characterization, in terms of their response to electrical fields at different excitation frequencies. After characterization, validation tests have been carried out on the actuators at low Reynolds numbers in the wind tunnel. Tests were done with an array of dimple actuators on a NACA4415 airfoil using PIV measurements. It has been found that the device is very effective in reducing flow separation which is of high relevance in MAV applications.

Nomenclature

C	=	Chord length of airfoil
C_d	=	Coefficient of drag
D	=	Diameter of cylinder
r	=	Radius of curvature of the dimple
R	=	Radius of the dimple
c	=	chord
α	=	Airfoil incidence angle
t	=	Thickness of conductor coating on EAP
T	=	Time period
x, X	=	Streamwise distances
Y	=	Longitudinal distances
θ	=	Angle subtended by dimple at centre of curvature

I. Introduction

Flight regime of small aerial vehicles like Micro Aerial Vehicles (MAVs) and Unmanned Aerial Vehicles (UAVs) fall under low Reynolds number regime of 10^5 or lower, where the phenomenon like Laminar Separation Bubble (LSB) and hysteresis are dominant. Flow separation and laminar–turbulent transition can result in substantial change in the effective airfoil shape and reduce aerodynamic performance [1]. A possible means of reducing this separation is through the application of flow control techniques. One of the techniques being currently pursued in the area of the control of laminar boundary layer separation is the application of static/dynamic dimples or depressions on the surface exposed to the flow (e.g., small depressions on the surface of golf balls). Dimples induce transition of the boundary layer by generation of streamwise vortices, leading to the alleviation of boundary layer separation.

Several studies have been carried out on the development and applications of Electro-active Polymer (EAP) based dimples for flow control [2-7]. These include the assessment of the suitability of EAP-based actuators both mechanically and aerodynamically with the ultimate goal of developing a integrate device (a flexible 'smart skin') and the study of the response of a laminar boundary layer to forcing using mechanical dimple [2,3], study on active dimple actuators for separation control using mechanically simulated dimples [4], study of the effect dimple depth and diameter on boundary layer separation control [4-5] and control of the separated flow field of a circular cylinder using dimples [6]. For the last few years, CSIR-NAL has been working in the area of the development of dimple actuators for Micro Air Vehicle (MAV). Emphasis has been given to the fabrication of ultrathin metal electrodes having compatibility with hyper elastic polymer films. This paper describes the design, fabrication, wind tunnel characterization and application of dimple actuators for flow separation control on low Reynolds number air foil.

II. Experimental procedure

A. Fabrication of Active Dimple Actuators:

Top and bottom circular metal electrodes of diameter 10 mm were fabricated on a 100 μm thick elastomer (MED-4905) using Ultra High Vacuum (UHV) sputtering systems. Ultra-thin films of silver of thickness 6 nm were deposited in a pre-stretched polymer of its 30% strain. A fabricated dielectric elastomer actuator (DEA) was then mounted on a polypropylene holder along with the lead wires (Fig 1). Dimple actuators were then excited by keeping one electrode at ground, while the voltage on other electrode was varied from 0 to 4.4 kV using a high voltage amplifier (Trek, model 609-E) and was fully controlled by a function generator. The displacement of the actuators was then recorded with AC excitation using both sine and square waves over a range of frequencies from 0.1 Hz to 1000 Hz. Out-of-plane deflection measurements were taken using laser displacement sensor (Micro-Epsilon, model *Opto NCDT 2300*). The experimental set up for studying the electrical characteristics of a dimple actuator was shown in Fig. 2. Validation of the dimples involved detailed mapping of the flow field on the baseline airfoil and airfoil with dimple actuators, done in the 0.2m wind tunnel, MAV Unit, using a *Dantec 2*D PIV system. The system consists of a 65mJ Nd:YAG double-pulsed laser, *Flowsense* 2048X2048 pixel camera and *Dynamic Studio* software for the acquisition processing of frames.

III. Results and discussion

A. Characterization of dimple actuators:

Electroactive polymer, is an hyperelastic materials (Elastic modulus ~ 0.24 MPa), forms dimples under electric fields in a restricted boundary. These polymer being an insulating dielectric materials, a compatible conducting electrodes are essential to charge/discharge the dielectric materials to produce an actuation. Metals electrodes with higher thickness (> 100 nm) was not only produces higher stiffness due to large rigidity modulus (few GPa), also developed several cracks while actuation under high electric fields. This causes the failure of the actuators with burning due to the arcing at crack points. We have sputtered ultrathin Ag metal film with thickness ~ 5-8 nm to serve as electrodes, and extensively studied the electromechanical properties. With bulge test method, it was shown that the elastic modulus changes marginally from 0.24 MPa to 0.7 MPa and even with 6 to 10 % strain (equivalent to bulge height of 1-1.5 mm for 10 mm actuator), there are no cracks in the films. The resistance was found to be in the ohmic (< 200 ohm) region even with 7 % strain. Under electrical field up to 4.4 MV/m with low frequency ~ 1 Hz, the displacement was achieved of the order of 150 to 200 μm (Fig . 3). However at resonance frequency ~ 1 kHz, a large displacement of the order of 300 μm was achieved.

B. Wind tunnel tests and validation of dimple actuators:

After successful testing of single actuator, actuator array was fabricated. Fabricated DEAs was mounted on airfoil to investigate the formation of vortices during wind tunnel testing. The array configuration consisted of five dimples (diameter: 10mm) with spacing of 20mm between centers; the connection diagram is shown schematically in Fig.4(a). The array was mounted on NACA4415 airfoil (c: 125mm, span: 195mm), as shown in Fig.4(b). The actuator array is located at ~30% of the airfoil chord, just ahead of separation location, which was indicated by flow r to be ~ 35% of the airfoil chord [8]. Measurements were made on the airfoil with and without the dimple actuators at free stream velocities of 4.3m/s and 9.3m/s; corresponding Reynolds numbers were 78,000 and 120,000 respectively. Results of the measurements on the baseline model and with dimple actuators at Re_c = 78,000 are shown for $\alpha = 6^o$ are shown in Figs.5 (a and b). It can be seen from Fig.5(a) that the flow separates at close to x/c of 0.35 without flow control and remains separated beyond 0.63c. (Subsequently it attaches at allocation about 0.7c, which could not shown in the plot). With the active flow control using dimple (excited at 4KV at a frequency of 100Hz), flow separation can be seen to be very nearly controlled, with very little reverse flow shown in Fig.5(b). At Re_c=120,000, however, the flow separation occurs much beyond 0.35c (near 0.42c); the height of reverse flow region is also reduced (Fig.6a). With dimple actuation, the flow now remains attached, as can be seen from Fig.6 (b). Figs.7 (a) and 7(b) show the flow fields on the airfoil at an incidence of 8^o without and with flow control respectively. As compared to the case of $\alpha = 6^o$, the separation occurs earlier (at ~0.3c) and is more pronounced. The dimple actuation is seen to be quite effective to control the separation; the effectiveness is as good or better the case of $\alpha = 6^o$. From the above discussion, it is has become clear that active dimples located ust upstream of separation location is an effective tool of separation control. This demonstrates the capability of the technique in the control of LSB, resulting in enhanced performance of the airfoil.

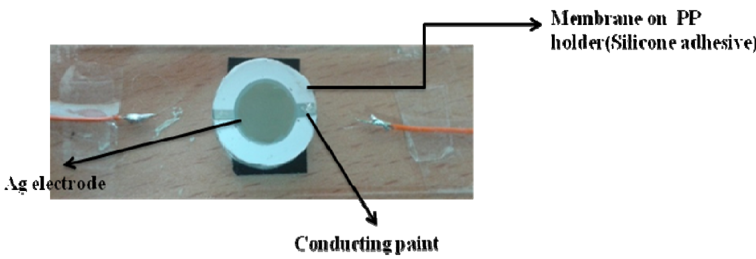


Fig.1 Dielectric elastomer actuator fabricated at NAL

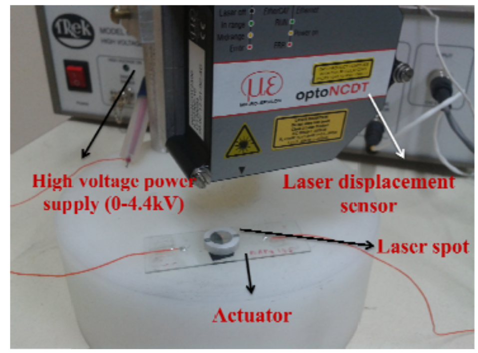


Fig.2 Schematic design to study the performance of dimple actuators

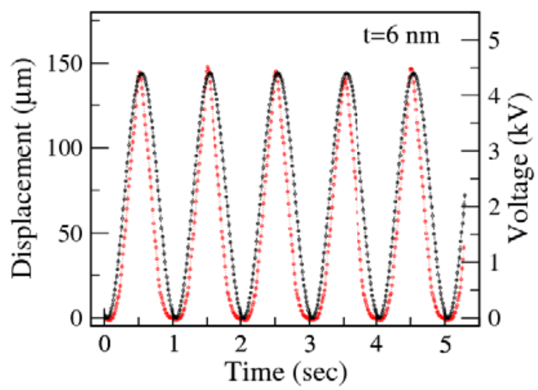
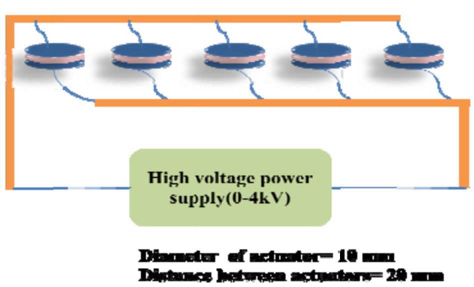


Fig.3 (a) Sine wave 1Hz frequency at 4.4kV



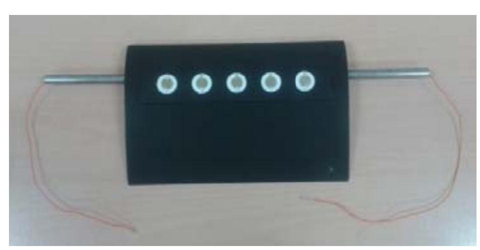
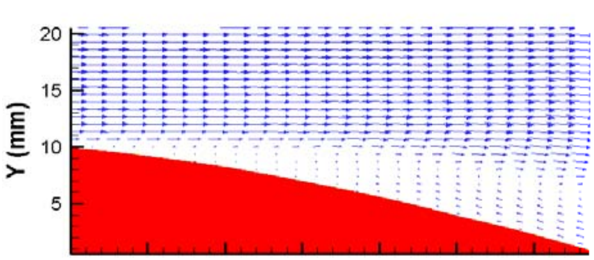
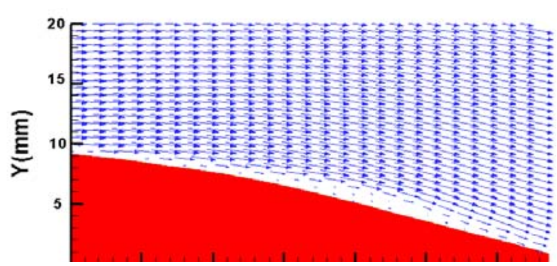


Fig.4 (a) Dimple array configuration and High-voltage supply connections (b) NACA 4415 airfoil with dimple actuators placed close to air separation.





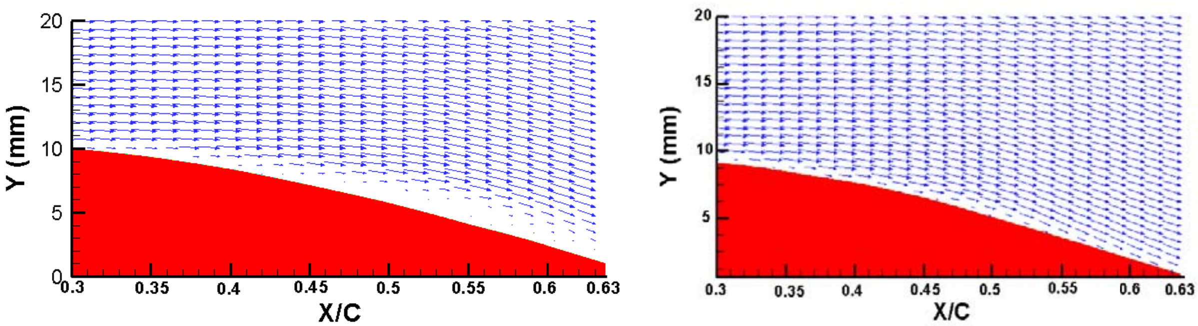


Fig.5 (a) Flow field of NACA 4415 airfoil without dimple actuation (b) with dimple array placed close to separation location actuated (4KV, 100Hz); α : 6°, Re_c : 78,000.

Fig.6(a) Flow field of NACA 4415 airfoil without dimple actuation (b) with dimple array placed close to separation location actuated (4KV, 100Hz); α : 6°, Re_c : 120,000

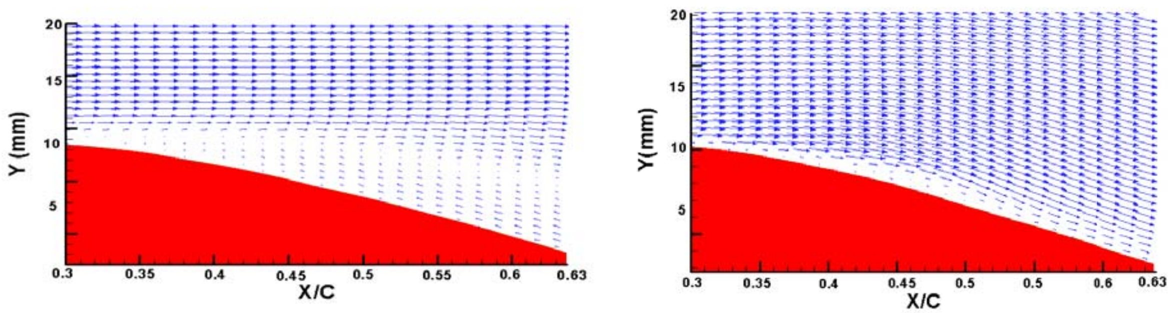


Fig. 7(a) Flow field of NACA 4415 airfoil without dimple actuation (b) With dimple array placed close to separation location actuated (4KV, 100Hz); α: 8°, Re_c : 78,000.

IV. Conclusion

Design, fabrication, validation and applications of EAP-based dimple actuators developed and are presented. These actuators have the potential applications on the control of low Reynolds number flows, where laminar separation bubble is present. The technique has the specific advantages of low weight and lower drag penalty, when used as a flow separation control; the devices can also be actuated “On Demand”; since the material can also be used as an actuators and pressure sensor, a *smart skin* having closed-loop flow control capabilities can be realized. The work involves multi-disciplinary approach, incorporating flow physics, mathematical modeling and simulation, advanced techniques in coating on polymer materials, sensors and actuators etc. After considerable efforts, dynamic dimples capable of achieving depths up to 147µm and oscillating at frequencies up to a KHz have been fabricated, characterized and tested at NAL. In order to establish the capability of the devices for control of flow separation, quantitative measurements using 2D-PIV has been carried out on a NACA4415 airfoil with and without flow control. Results of the flow field mapping have shown that the flow gets attached and length of LSB is reduced in the presence of flow control.

Acknowledgments

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